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SEMICONDUCTOR PHASE CONJUGATION

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The HYWAYS PEP pilot line validated the producibility of long wavelength infrared hybrid sensor arrays with Si:As impurity band conduction detectors and advanced capacitance transimpedance amplifier readouts. The production capacity for processing, packing, and testing 10 hybrids/day was established. Ninety hybrids were delivered. Hybrid sensor arrays designed to Ground-based Surveillance and Tracking System specifications were processed, which satisfied interim proof-of-design requirements. A mathematical model was delivered that estimates the cost of long wavelength infrared hybrid sensor arrays based on format, quantity, and protected yield.

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1.0 PROJECT SUMMARY, METHODS AND PROCEDURES

This effort consisted of both theoretical and experimental studies of multiwave mixing processes in highly nonlinear media in the steady state and transient regimes. The emphasis was millisecond-nanosecond (ms-ns) laser pulse-induced nonlinearity, nonlinear optical processes and devices mainly in the 1.06 μm spectrum using primarily liquid crystals and semiconductors (e.g., Si, GaAs). Because possible future applications in other wavelength regions (e.g., 0.8 μm in MQWs, 1.3 μm and 1.5 μm regions) and other time scales e.g., picosecond (ps) are of interest general features of the processes were also under study. The following topics were studied:

- Probe beam amplification via thermal and orientational nonlinearity in liquid crystals, and electronic nonlinearity in Si and GaAs, using multiwave mixing effects (detailed theory and experiments).

- Wavefront conjugation with gain and related image amplification and wavelength conversion processes, using liquid crystals and semiconductors.

- Fundamentals of the dynamics of the nonlinear medium response and the electrodynamics of the multiple-beam propagations and coupling within a general nonlinear medium: theory and experimental confirmation.

Considerable emphasis was also placed on the use of a CO_2 (10.6 μm) laser in the far infrared (IR), in the effort to fully develop the potential of liquid crystals as efficient IR nonlinear materials. In great contrast to the visible and near IR regime, there are relatively few highly nonlinear optical materials in the IR regime that are suited for the useful nonlinear optical processes mentioned above. Studies of solid state materials, gases, and other materials at 10.6 μm have shown that either the nonlinearity is small (therefore requiring high intensity lasers) or is large (requiring cryogenic temperatures or exact frequency tuning). Study of Indium Antimonide with a CO_2 laser (~5 μm) shows that the nonlinearity is very large but again a cryogenic temperature is required. Another equally important point about using long wavelength lasers is the proportionally smaller scattering loss owing to the liquid crystal director axis orientation fluctuations. The scattering loss is dominated by the orientation fluctuations and decreases as the wavelength is increased, roughly as the square of the inverse wavelength (i.e., λ^{-2}). At 10.6 μm, there is negligible scattering loss for a typical liquid crystal film thickness ($\lesssim$ 100 μm).

This research program is among the first to fully document the application of these newly observed nonlinear processes in thin media (e.g., wavefront conjugation with gain, beam amplification, ring-oscillators, phase-locking, image conversion, etc.), the fundamental problems involved, and possible device development.

The parallel studies involving visible lasers and near IR (around 1 μm) lasers will addressed several fundamentally interesting questions which also have practical impact. One problem with nonlinearities caused by diffusion (e.g., thermal in liquid crystals and electronic in semiconductors) is the intrinsically nonlocal nature of the response under laser excitation: both are dependent on the boundary conditions (e.g., cell walls, grating spacing, laser beam size diffusion constants, recombination, etc.). A "local" response depends on the local optical electric field/intensity. A detailed knowledge of the nonlocal behavior is important not only in such "obvious" effects such as transverse phase modulation and bistability effects, but also vitally important in all wave mixing processes involving the growth of the generated signal with the interaction length (from the entry plane to the exit plane). Diffusion of heat in all relevant directions in liquid crystal (grating maxima to minima, cell wall to cell wall, etc.), in electron-hole diffusions and recombinations, or in excitons in semiconductors, will all be manifested in one important form or another in these wave mixing processes. A simple example is the sensitive dependence of these mixing processes on the grating constant and the sample thickness seen in some of the reported experiments. The self-consistent, accurate way to describe these processes is with the coupled electrodynamical equations and the heat equation and/or the coupled electron-hole density and temperature equations. The research focused on the diffusion effects on optical beam amplifications and phase conjugation with gain in liquid crystal films involving short pulses, and on other nonlinear mediums involving some diffusion processes (especially those in semiconductors involving electron-hole diffusions and excitonic dynamics).

2.0 STATEMENT OF TASKS

2.1 BASIC PROGRAM (FIRST YEAR)

The contractor investigated degenerate multiwave mixing theories and experiments in highly nonlinear media such as liquid crystals and semiconductors. A general theory was developed that accounted for both steady state and transient energy coupling between the input beams, and various physical parameters such as self-phase modulations, intensity dependent phase shifts, pump beam depletion and losses, and saturation effects. Experimentally, the amplification of the signal wave via the multiwave mixings effects was studied for the steady state regime with continuous wave (cw) visible and IR lasers, and for the transient regime with ns-pulsed visible and IR lasers.

2.2 PHASE 1 (FIRST YEAR)

The contractor employed a set of complex phase and amplitude coupled Maxwell wave equations to quantitatively elucidate the effects and interrelationships of various optical, geometrical, and physical parameters involved in the multiwave mixing process. Experimentally, the probe beam gain was studied as a function of the laser pulse length versus the medium response time, i.e., for cw and transient wave mixings. Experiments were designed to probe the critical role played by laser beam intensity, intensity ratio, phase mismatches, frequency shifts, temperatures, interaction length and geometry and material characteristics.

2.3 PHASE 2 (SECOND YEAR, OPTION 1)

The contractor performed image-bearing-beam amplification and reconstruction with visible, near IR and far IR laser sources. Reconstruction of the image beam in a different wavelength (i.e., image conversion) was also be studied, as well as the image resolution and amplification linearity. Saturation effects and optimal configuration for efficient amplification for cw and pulsed laser sources were investigated.

2.4 PHASE 3 (THIRD YEAR, OPTION 2)

The contractor performed further experiments with phase conjugation and the associated amplified reflection effect, and examined the role played by various optical, physical, and geometrical parameters in multiwave mixing mediated optical phase conjugation. In particular, the difference from and the advantage of these multiwave mixing processes over the usual four wave mixing mediated phase conjugation processes were thoroughly explored. The possibility of realizing optical phase conjugation self-oscillator, ring oscillator and phase-locked oscillator was examined.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The 3-year program resulted in several first time studies, addressed all the proposed tasks, and opened up new avenues for future research. Accordingly, a white paper proposal entitled "Stimulated scatterings and wave mixings in liquid crystal fiber waveguides and thin films for broadband nonlinear optical applications," has been submitted in July to Phillips Laboratory, KAFB. The essence of this new proposal, summarized below, constitutes the conclusions and recommendations.

3.1 PROJECT SUMMARY

It is recommended that the following projects be conducted in a future program: stimulated Brillouin and thermal scatterings in thin films and long (specially fabricated) liquid-crystal-cored fibers and the associated phase conjugation, beam/image amplification and other nonlinear guided-wave propagation effects (pulse narrowing, harmonics generations); and transient two- and multi-wave mixings and their applications in various optical beam/image processing and modulation applications. These studies will be conducted using a variety of liquid crystals (nematic, smectic and isotropic) known to exhibit special/highly nonlinear optical responses, in conjunction with a broad range of lasers, ns, ps, and cw, in the visible, near IR and far IR regimes. Several new and useful nonlinear optical processes, nonlinear materials in several configurations (fibers, thin films), and devices (wave mixers, phase conjugators, pulse shapers and harmonics generators), which are applicable over a broad spectral range (visible-far IR) and time scales, are the expected result of this program.

3.2 TECHNICAL PROJECTS AND ANTICIPATED RESULTS/PAYOFFS

Current research and development in optical signal/image processing, switching, and communication are spurred and largely governed by advances in materials (their synthesis and processings) and the underlying optical processes (innovative use of standard ones or newly discovered ones). This proposal is focused on several newly observed nonlinear optical parametric processes of great application potential in the mesophases of liquid crystals (resulting from the current Air Force Program), when the latter are fabricated in special thin film or long-fiber forms. Specific projects, the approaches, and the anticipated results/payoffs are summarized below.

3.2.1 Simulated Thermal Scatterings and Novel Wave Mixings

Owing to their unique birefringent and bipolar (possessing both positive and negative nonlinearities) properties, and their extraordinarily large thermal index gradients, nematic liquid crystals in their usual thin film form have been recently shown to be excellent materials for a variety of cross-polarization wave mixing processes (Refs. 1, 2, 3,and 4). There are several attractive features of these processes: (i) applicable over a wide spectral range, and to other materials as well; (ii) simultaneous polarization switching and beam amplification effects that facilitate high signal/noise ratio and contrast; (iii) involve only a pump and a probe beam, i.e., a two-wave mixing configuration suitable for a self-pumped phase conjugator or oscillator, and applicable to degenerate and nondegenerate frequency beams. The proposed studies will address several hitherto unanswered theoretical issues regarding these new birefringent wave mixing effects (e.g., their temporal intensity-, geometrical-, optical-, and material-parameter dependences; the influence of pump beam depletion, beam intensity ratio, and phase conjugation characteristics). This analysis will be corroborated by parallel experimental measurements using a variety of lasers (visible, near

IR, IR) for time scales ranging from cw to ns. The objective is to conclusively document this new class of parametric processes, and to demonstrate their general applicability to other synthetic or naturally occurring birefringent nonlinear optical materials (e.g., semiconductor quantum wells and photorefractive crystals). In the latter context, some exemplary experiment with photorefractive materials will also be performed.

3.2.2 Nonlinear Liquid Crystal Fiber and Stimulated Brilloui- Scatterings

As a result of previous and more recent work (Refs. 5, 6, 7, and 8), liquid crystal cored fibers can be fabricated. Recently, unusually large density wave contributions have been observed in dynamic scatterings in some specially doped chiral nematic liquid crystals in their isotropic phase, which corroborated the previous observations of stimulated scatterings and phase conjugation in similar materials.

These observations, and the feasibility of fabricating long (as long as commercially available capillary tubes, e.g., tens of cms) liquid crystal cored fibers (which have low loss for core diameters: <10 μ with nematics; the isotropic phase even smaller) open up several avenues for nonlinear optical studies with great potential payoffs. From the numerous projects possible, the focus here will be on the process of Stimulated Brillouin Scattering and Wave Mixing in such liquid crystal cored fibers.

In the proposed projects, several liquid crystal (pure, mixed, specially doped or dyed) in nematic, smectic, or isotropic phase, which are known to exhibit large nonlinearities (especially their density component), will be drawn into capillary tubings of various lengths, core diameters, and surface alignments. Their physical, optical and nonlinear optical characteristics will be quantitatively documented, followed by stimulated Brillouin enhanced two-wave mixing experiments with ns and ps Nd:Yag lasers (both the fundamental 1.06 μ and the second harmonic at 0.53 μ will be used). When the interaction length, core dimensions (for single or multi-mode coupling/wave guiding), optical intensity, dopants, and other liquid crystal parameters (absorption, electrictive coefficient, molecular correlations near their phase transition temperatures, etc.), are varied these previously observed stimulated scattering effects are expected to assume a rich variety of useful/efficient forms, and bring forth new fundamental understandings.

Owing to their anisotropic and nonlinear properties in the ns and ps time scales, as reported recently (Ref. 8), it is reasonable to expect that, in guided wave propagation, many interesting/new effects (e.g., pulse narrowing, phase modulations, etc.) may also be involved. Some liquid crystals in their nematic phase, e.g., 4-4' -Bis(heptyloxy) azoxybenzene, have also been observed to exhibit unusual polarization dependence. By using doping techniques, or mixtures, this high temperature nematic may be used in conjunction with other more standard temperature nematics for fabricating long liquid crystal cored fiber, and observation of polarization selective or cross-polarization wave mixing effects. These studies will add both excitement and payoffs to this program.

4.0 RESULTS

In short, this research program has been very successful, and all major proposed tasks were accomplished. The following is a list of technical publications and conference presentations which acknowledge support from this program. These publications include results obtained through efforts funded by more than one agency; the other two agencies are the National Science Foundation and the Defense Advanced Research Project Agency. An asterisk (*) is placed on publications where the major support is from the Air Force .

4.1 PUBLICATIONS

4.1.1 First demonstrations of efficient wave mixing mediated beam amplifications in Kerr media

- IR: I. C. Khoo, P. Y. Yan, G. M. Finn, T. H. Liu and R. R. Michael, "Low power (10.6 μm) laser beam amplification via thermal grating mediated degenerate four wave mixings in a nematic liquid crystal film," J. Opt. Soc. Am. B5, 202, 1988.
- Visible: I. C. Khoo and T. H. Liu, "Theory and experiments on multiwave mixing mediated probe beam amplification," Phys. Rev. A39, 4036, 1989.
- *Theories: P. Y. Yan, and I. C. Khoo, "Stationary and moving thermal grating mediated infrared laser wave mixing and amplification in nematic liquid crystal films," IEEE J. Quant. Electron. QE25, 520, 1989.

4.1.2 First demonstrations of multiwave mixing effects on optical phase conjugations

- *Theory: I. C. Khoo and Y. Zhao, "Probe beam amplification and phase conjugation self-oscillation threshold in a thin Kerr medium," IEEE J. Quant. Electron. QE25, 368 (1989).

I. C. Khoo and W. Wang, "Effects of diffractions and self-phase modulations on phase conjugation self-oscillation in Kerr media," IEEE J. Quant. Electron. QE27, 1310 (1991).

- *Experiment: I. C. Khoo, R. Normandin, T. H. Liu, R. R. Michael, and R. G. Lindquist, "Degenerate multiwave mixing and phase conjugation in silicon," Phys. Rev. B40, 7759 (1989) -ns pulses in si.

4.1.3 First complete study of transient multiwave mixing effects in Kerr media with diffusive nonlinearities

- Theory: I. C. Khoo and P. Zhou, "Transient multi wave mixing in a nonlinear medium," Phys. Rev. A41, 1544 (1990). General theory for Kerr Medium - also specific theories for semiconductor (Si) and liquid crystals
- *Experiment: I. C. Khoo, P. Zhou, R. G. Lindquist, and P. LoPresti, "A quantitative analysis of picosecond transient multiwave mixings mediated beam amplification effect in silicon," Phys. Rev. A41, 408 (1990). On ps pulses in Si. I. C. Khoo, "Transient and stationary wave mixing and interface switching with liquid crystals," Molecular Crystal and Liquid Crystals 179, 163 (1990). (Liquid crystal with CO_2 laser.)
- *Recent experiments with ps pulses in GaAs - manuscript in preparation.

4.1.4 First theory and preliminary experimental observation of beam amplification and polarization switching on birefringent nonlinear material

• Theory: Phys. Rev. A42, 5528, 1990

Phys. Rev. Letts. 64, 2273, 1990

• Experiment: Manuscript in preparation. (Also, submitted to CLEO '91.)

4.1.5 *Detailed theory and some experimental confirmations of degenerate multiwave mixing and ring-laser oscillation in a Kerr medium (Optical Soc. Am. B8, 1433 (1991)

4.2 GRADUATE THESES AND DISSERTATIONS

- One Masters Thesis - Robert J. Mansfield (now at EGLIN Air Force Base)
- One Ph.D. Dissertation - Robert R. Michael (now at BDM, McLean, VA)
- One Ph.D. Dissertation - Rose W. Wang, Dec. 1991

4.3 CONFERENCE PRESENTATIONS

4.3.1 Invited Talks

- Transient and stationary optical wave mixing and interface switching with liquid crystals. I. C. Khoo, International Seminar on Physics of Liquid Crystals, Bra, Italy (Oct. 1988).
- Optical wave mixing and phase conjugation in silicon revisited. I. C. Khoo, 1989 Winter Colloquium on Physics of Quantum Electronics, Snowbird, UT.
- IR optical nonlinearities and novel two-wave mixing effects in nematic liquid crystals. I. C. Khoo, Joint Australian Conferences on Optics, Lasers and Spectroscopy (Sept. 1989).
- Stationary and transient multiwave mixing in liquid

crystals. I. C. Khoo, Lasers '89, New Orleans (Dec. 1989).

- Polarization switching and mixing with non-Lagrangian nonlinearity in birefringent Kerr-like and photorefractive media. I. C. Khoo, invited talk, International Conference on Lasers '90, San Diego (December 1990).

4.3.2 Contributed Talks

- Effects of side diffraction and phase modulation on optical multiwave mixing and phase conjugation. I. C. Khoo et al., Optical Society of America Annual Meeting, Santa Clara, CA (Nov. 1988).
- Effects of side diffractions, phase modulations and losses in phase conjugation. I. C. Khoo et al., Conference on Lasers and Electro-Optics, Baltimore (April 1989).
- Self-pumped multiwave mediated ring-oscillation and phase conjugation with Kerr-like nonlinear media. I. C. Khoo et al., Annual Meeting of the Optical Society of America, Orlando, FL (Oct. 1989).
- Experimental and theoretical study of transient multiwave mixing in nonlinear medium. R. G. Lindquist, P. Zhou, P. LoPresti and I. C. Khoo, Annual Meeting of Optical Society of America, Boston (November 1990).
- Novel polarization switching and beam amplification effects in birefringent nonlinear media. I. C. Khoo and Y. Liang, Annual Meeting of Optical Society of America, Boston (November 1990).

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8. Khoo, et al., "Dynamics of picosecond laser induced density, temperature and flow-reorientation effects in the mesophases of liquid crystals," J. Appl. Phys., 69, 3853 (1991).